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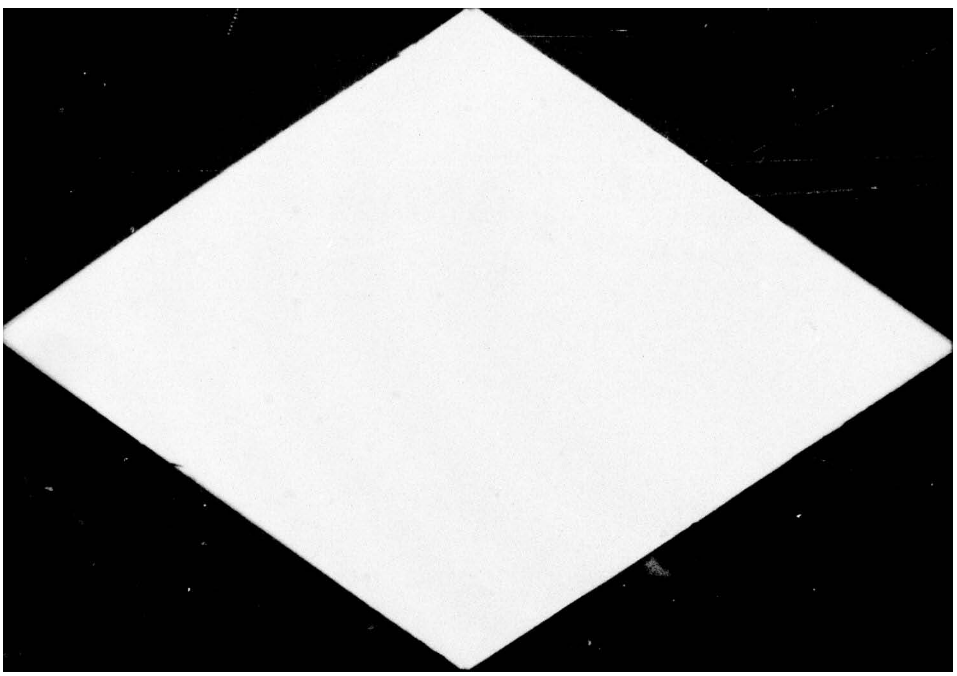

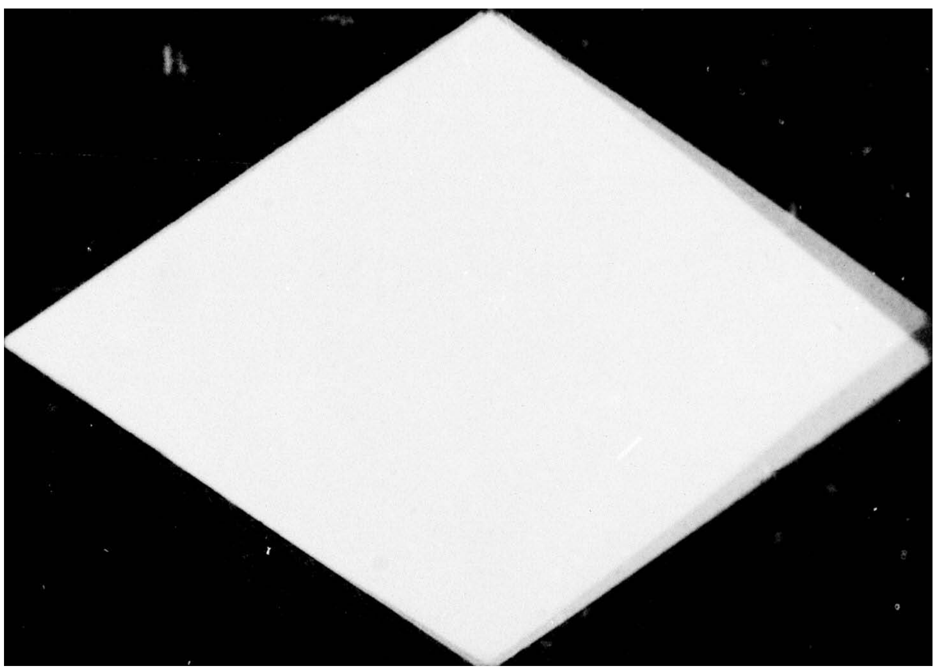

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DESIGN OF PRACTICAL CONTROL ALGORITHMS FOR NONLINEAR STOCHASTIC SYSTEMS

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Prepared by

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Operations Research INformation CONtrol

The problem of stabilization and control of nonlinear stochastic systems observed by noisy measurement data arises in many Air Force system applications. Inherent in this problem is the problem of processing noise-contaminated measurement data to obtain accurate estimates of the state of the system. If it is possible to estimate the state of the system accurately, then well-known classical deterministic control techniques may often be used to give adequate system performance. This approach will greatly reduce the complexity of the control algorithm over that required by a truly "optimal" stochastic control policy. On the other hand, the use of recently developed filtering techniques in place of the simpler linearized or extended Kalman filters can greatly increase the accuracy of the state estimates and; thereby, improve system performance and alleviate divergence problems.

A straightforward approach to the stochastic control problem would be to use the recent research results giving approximate a posteriori densities in conjunction with the principle of optimality in order to solve the optimal control problem using the well known stochastic dynamic programming equations. Preliminary studies of this approach show two things. First, even for very simple systems in which it is possible to obtain tractable approximate densities, it is very difficult to obtain solutions for even approximate controls in this manner. Secondly, even though the control algorithms developed can in no way be considered practical because of the extensive calculations involved, they can lead to greatly reduced cost even for very simple problems. This second factor does make the continued investigation of the stochastic control problem interesting, but the first indicates another approach should be used.

The approach taken in this contract has been to investigate the effect of already developed nonlinear filters in the feedback

loops of nonlinear stochastic control systems to be followed by optimal or nearly optimal deterministic controls. This in effect can force the separate structure of the linear quadratic Gaussian problem on the more general nonlinear stochastic control problem, but will make use of the latest developments in the field on nonlinear estimation. In particular, nonlinear measurements of basically linear systems will be investigated since the cost of transducers often increases markedly from the linearity constraint. It may be that the cost of a small computer in a control loop could be completely saved by a reduction in the cost of the transducers required.

Work on this contract has allowed continued investigation into the development and use of nonlinear filters in conjunction with deterministic control laws. Much of the detail on the work performed under Contract AFOSR-F44620-75-C-0023 is contained in the publications listed below, which have been published, accepted or submitted since the beginning of this contract.

(1) Alspach, D. L., "A Gaussian Sum Bayesian Approach to Passive Bearings only Tracking," Invited Paper Proceedings of the Office of Naval Research Sponsored Conference on Target Motion Analysis held at Monterey Naval Postgraduate School, May 25-27, 1977.

(2) Alspach, D. L. and H. W. Sorenson "Approximate Solutions of the Nonlinear Filtering Equations," invited chapter in forthcoming book Nonlinear Estimation and Filtering Theory: A Status Review, edited by E. Stear to be published by Marcel Dekker.

(3) Alspach, D. L., "A Discussion of the Relationships Between the Dual Goals of Stochastic Control," Pergamon Press, An International Journal of Computers and Electrical Enginering, Vol. 4, No. 1, January, 1977.

(4) Alspach, D. L., "A Stochastic Regulator Using a Certainty Equivalence Control with a Nonlinear Filter for Processing Hard-Limited Data," Information Sciences, Vol. 13, 1978

(5) Scharf, L. L. and D. L. Alspach, "Nonlinear State Estimation in Observation Noise of Unknown Covariance," International Journal of Control, 1978

(6) Scharf, L. L. and D. L. Alspach, "Nonlinear State Estimation in Observation Noise of Unknown Covariance," Proceedings of the 1976 Joint Automatic Control Conference (West LaFayette, Indiana, July 27 - 30, 1976).

(7) Alspach, D. L., "Nonlinear Filters in Feedback Control," Proceedings of the Sixth Symposium on Nonlinear Estimation Theory and Its Applications, San Diego, California (Sept. 1975).

(8) Alspach, D. L., "A Certainty Equivalence Control with a Nonlinear Filter in the Feedback Loop," Proceedings of the 1975 IEEE Symposium on Decision and Control, Houston, Texas (December 10-12, 1975).

(9) Alspach, D. L., "A Stochastic Control Algorithm for Systems with Control Dependent Plant and Measurement Noise," An International Journal of Computers and Electrical Engineering, Vol. 2, No. 4, November 1975.

(10) Alspach, D. L., "A Gaussian Sum Approach to the Multitarget Identification-Tracking Problem," Automatica, Vol. 11, pp. 285-296 (August 1975).

Only a brief outline of the work contained in the above publications is given here.

A specific application of the use of Gaussian sums to the bearings only target motion analysis problem was presented at the Naval Postgraduate School in Monterey. This invited paper was published in the Proceedings of the conference, the main theme of which was bearings only target motion analysis.

A summary/review paper was prepared as an invited chapter of a text on nonlinear estimation, edited by Dr. E. Stear. The paper is entitled "Approximate Solutions of the Nonlinear Filtering Equations" and the book will be entitled "Nonlinear Estimation and Filtering Theory: A Status Review." The work done on the contract to date including that in the publications above will be summarized in some detail in this review chapter, as well as work by other workers in the field.

A general philosophical approach to stochastic control is discussed in (3) above. The method of aligning the "dual" goals of the general optimal stochastic control as a design tool is discussed. When the two goals are exactly aligned, the certainty equivalence control is optimal and no additional intentional "probing" is required. If these goals are "anti-aligned," demanding opposing controls, the certainty equivalence control can be, locally at least, the worst control possible. An exampl e with this characteristic has been discussed in publication (3).

In publication (4) we consider a simple example of a nonlinear filter in a feedback loop. For this case the "dual goals" are aligned and it is shown that the performance of the system is very close to that of an optimal stochastic control. Since the optimal stochastic control algorithm is very difficult to calculate, this is done by comparing the performance to a known lower bound. This lower bound is found in the following manner. It is clear that there is more information about the state in a linear measurement of the state contaminated by noise $z_{LIN}(k)$ than in the hard-limited version $y_{HL}(k)$:

$$z_{LIN}(k) = H_k x_k + v_k$$

$$y_{HL}(k) = SIGN(z_{LIN}(k)) = SIGN(H_k x_k + v_k) \ .$$

With the linear measurement function, the optimal stochastic control is given by the separation theorem. It is clear that the performance of the optimal stochastic control system with only the hard-limited function $y_{HL}(k)$ available will be worse than the system with the linear function $z_{LIN}(k)$. It is shown in publication (4) that given only $y_{HL}(k)$, the performance of the certainty equivalence control with a nonlinear filter is close to that of the optimal control system with the better linear measurement.

In publication (5) and (6), a new nonlinear filter was developed in conjunction with Dr. L. Scharf of Colorado State University. This paper considers the adaptive Kalman filtering problem where only the measurement noise covariance is unknown. A new parallel filtering algorithm is developed.

In publication (7), the effect of control-dependent plant and measurement noise on the feedback control is discussed. It is shown that the goals are effectively aligned, but not of the same magnitude. The use of any control action reduces the accuracy of the state estimates. Thus, the effect of such control-dependent noise is to induce "caution" on the control.

In publication (8), the filter for processing hard-limited measurement data was first introduced. In publication (9), a filter for state estimation in systems with state and control-dependent measurement noise was introduced. In publication (10), Gaussian sum filters are used in a Bayesian approach to the multitarget tracking problem.

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This interim report summarizes a continuation of the investigation into the use of digital nonlinear filters in conjunction with deterministic control algorithms. The problem of stabilization and control of nonlinear stochastic systems observed by noisy measurement data arises in many Air Force systems. Inherent in this problem is the problem of processing noise contaminated measurement data to obtain accurate estimates of the state of the system. If it is possible to estimate the state of the system accurately, then well-known

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20. Abstract

classical deterministic control techniques may often be used to give adequate system performance. This approach will greatly reduce the complexity of the control algorithm over that required by a truly "optimal" stochastic control policy. On the other hand, the use of recently developed filtering techniques in place of the simpler linearized or extended Kalman filter can greatly increase the accuracy of the state estimates and, thereby, improve system performance and alleviate divergence problems.